Appendix B
A Review of State-of-the-Art Techniques for Real-Time Damage Assessment of Bridges

B-1. Introduction

a. It was reported that, as of November 1991, 35 percent of approximately 590,000 bridges in the United States were considered structurally deficient or functionally obsolete (Bagdasarian 1994). Many bridges have become deficient due to increased age and larger than expected service loads. In addition, some highway and railroad bridges ranging from 50 to more than 100 years old are still performing their intended function in spite of excessive use (Scalzi 1988). AASHTO has developed a "Manual for Condition Evaluation of Bridges" (1994), which provides for uniformity in the procedures and policies for determining the physical condition, maintenance needs, and load capacity of highway bridges. Recent bridge collapse or near collapse has focused the need to develop extensive nondestructive evaluation (NDE) techniques for real-time structural damage assessment to guarantee the safety of our nationwide transportation system. Real-time NDE techniques can immediately provide information such as size, shape, location, and orientation of discontinuities as part of the structural damage assessment.

b. NDE techniques for material inspection have been well-known for many years (Krautkrämer and Kratkrämer 1977; Lord 1980; Lew 1988; Bray and McBride 1992). They include liquid penetrant, eddy current, radiography, magnetic particle, ultrasonic, acoustic emission, and dynamic property measurement methods. Among those, ultrasonic and acoustic emission technologies have become the most popular and frequently used to perform real-time inspection. The dynamic property measurement method has also been used to evaluate the integrity of structures.

c. Applications of dynamic property measurement techniques in civil engineering (e.g., buildings, bridges, and dams) are rather rare. Although the acoustic emission technique was suggested in the 1970s to monitor a military bridge (Pollock and Smith 1972) and to detect discontinuities in steel highway bridges (Hutton and Skorpik 1975), it was only successful in a limited number of instances (Fisher and Wood 1988). The reason for this may be multi-fold since NDE is an interdisciplinary technology. It involves mechanical, electromagnetic, acoustic, and optical techniques to evaluate the integrity of a structure. When it is used for civil engineering applications, such as bridge damage assessment, the discontinuities to be detected may be large in dimension but complex in structure. Moreover, the inspections are subjected to environmental influence such as weather and noise. Accessibility is also more of a challenge when performing field NDE on in-service bridges as opposed to inspecting items mass produced in a factory. In addition, there is less of a tendency for bridge features to be standardized relative to mass produced factory items. Consequently, "standard" NDE procedures for bridges typically do not exist but must be uniquely developed for each application. Nevertheless, with the combined strength of both the NDE tools and the civil engineering professionals, progress is being achieved in damage assessment of bridges.

d. Appendix B provides a brief review of NDE fundamentals and discusses their application towards evaluating fracture critical members (FCMs) on bridge structures. The principles and general applications of each technique are emphasized along with newly reported bridge field testing applications. Detailed knowledge pertaining to the physical bases and instrument operation procedures for each technique can be found in Krautkrämer and Krautkrämer (1977) and Bray and McBride (1992).

B-2. Some New NDE Techniques in Real-Time Structural Damage Assessment

a. Eddy current method.

(1) Principle.

(a) The eddy current method is based on the fundamental work of Farady, Oersted, and

Maxwell (Libby 1971). An electrical current flowing in a wire generates an electromagnetic field about the wire. The electro-magnetic field becomes concentrated when the wire is wound in the form of a coil. Such coils are used for the eddy current testing of materials. When an energized coil is placed near the surface of metallic material, eddy currents are induced in the material. Coil current must be alternating (ac), since relative motion between the field and conductor is required to generate or induce electricity. Current induced in the metal flows in a direction opposite to the current in the coil. Material properties as well as discontinuities, such as cracks or voids, will affect the magnitude and phase of the induced current. Thus, with the aid of suitable instrumentation, eddy currents can assess the material conditions. Typical test coil arrangements are shown in Figure B-1.

(b) The eddy current inspection method has numerous favorable characteristics that make it the proper choice for many inspection tasks. Primary among these advantages is that mechanical contact is not required between the eddy current transducers and the test articles. Eddy current penetration depth and, consequently, inspection depth can be controlled by adjusting the frequency of energizing current. The method has high sensitivity to small discontinuities. Dimensional measurements and electrical conductivity measurements can also be made. Instrumentation for eddy current testing is relatively low cost for most applications. The equipment can be automated for high-speed testing with lightweight portable instruments.

(c) Eddy current techniques are limited in that only electrically conductive materials can be tested. There is limited material penetration with high-frequency energy, and discontinuity indications are largely qualitative. The many material, geometric, and electronic parameters affecting test results often complicate data interpretation. Thus, considerable care must be exercised in selecting eddy current techniques and in evaluating inspection results to avoid interpretation errors.

(2) Applications.

(a) As early as the late 1930s and early 1940s, investigators began the application of eddy current techniques to materials evaluation problems. Commercial instruments became available during this time and were used extensively during World War II.

(b) With the rapid development of electronics and computer science, presently the eddy current technology can be utilized to assess selected material properties as well as locate discrete discontinuities in metallic structures such as aircraft (Hugemaier 1991), coolant channel assemblies of nuclear reactor (Bhole et al. 1993), large diameter pipeline steels (Nestleroth 1993), etc. A list of selected applications is given in Table B-1.

(c) The establishment of accept/reject criteria for discontinuities is a matter of specifying how many discontinuities are acceptable, what size and how close together they are, if they can be allowed in engineering components of each class, material thickness, type of material, type of weld, size of structure, and service condition. Acceptance criteria are highly item oriented.

(3) Inspection of bridges.

(a) Although not commonly used in inspecting steel bridges, eddy current method was reported to have been used to inspect steel bridges in Japan (Kishi and Ohtsu 1988). The onsite eddy current system used for steel highway bridges has advantages such as, clear reproduction of results, high inspection speed, no coating removal required, and feasiblity for noncontact applications. However, there are still some problems in using eddy current methods to inspect welded members in steel bridges. One problem is the presence of noise in the electric current during field testing. Electronic noise signals can hamper the inspector’s ability to identify discontinuities. Another concern is the significant disturbance from the spatial distribution of welded

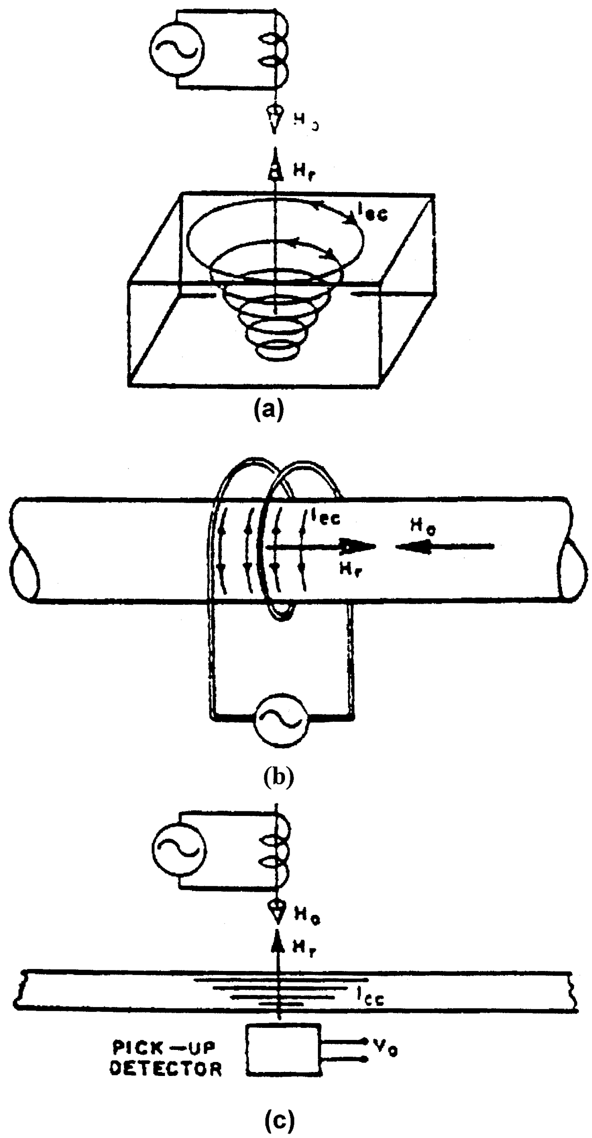


Figure B-1. Arrangements of eddy current test probes and test objects for (a) probe on one side of test object, (b) probe encircling test object, and (c) excitation and pick-up on opposite sides of test object

Table B-1
Typical Applications of Eddy Current Inspection

Material Property Determinations
Heat treatment evaluation
Hardness measurements
Fire damage determinations
Impurity content measurement
Discontinuity Detection
Sheet metal
Foil
Wire
Bar
Tube Testing
Bolt inspection
Weld inspection
Ball bearings tests

reinforcement, which makes the separation between signal and noise also difficult to interpret. These problems are circumvented by self-compensating the permeability difference between weld metal and base metal and by minimizing noise signals due to reinforcement distribution.

(b) Eddy current signals from different types of discontinuities in steel girders are shown to be remarkably different, which may give useful information pertaining to structural damage assessment. Unfortunately, detailed information on measurements and interpretations of these signals have not been reported. Additional information on the eddy current method can be found in Bray and Stanley (1989) and AWS (1980).

b. Vibration dynamic method.

(1) Principle.

(a) Certain properties of structures can be evaluated using vibration dynamic techniques. It is well-known that a structure possesses certain natural vibration frequencies and mode shapes. If friction is taken into account, the vibrations that are already excited will decrease gradually. This is called a damping vibration. The dynamic vibration tests are carried out by applying a known forced vibration to the structure and observing its vibration response. The fundamental concept is to compare to measured dynamic response with either the dynamic response predicted by an analytical model or the previously measured dynamic response.

(b) Theoretically, any discontinuities, cracks and other variations in structural properties will alter the vibration characteristics of the structures. Changes in vibration measurement may be used for structural damage assessment and monitoring bridge integrity. However, difficulties in modeling the restraint from supports as well as other modeling difficulties can preclude the comparison of modeled versus measured dynamic response to identify the subtle effects of cracks. In addition, environmental effects such as thermal expansion or debris collecting at expansion joints can also overshadow subtle changes in dynamic response due to the presence of cracks when comparing dynamic response to previous responses.

(c) Some fundamental modes of vibration for a very simple structure are illustrated in Figure B-2, which shows a fundamental flexural (a) and longitudinal (b) mode of vibration of a rectangular bar. For the flexural mode, the particle excursions in the material are vertical through the bar length; conversely, the particle excursions for the longitudinal mode are in the direction of the bar length. The natural vibration frequencies for these two modes can be written respectively as (for a square bar):

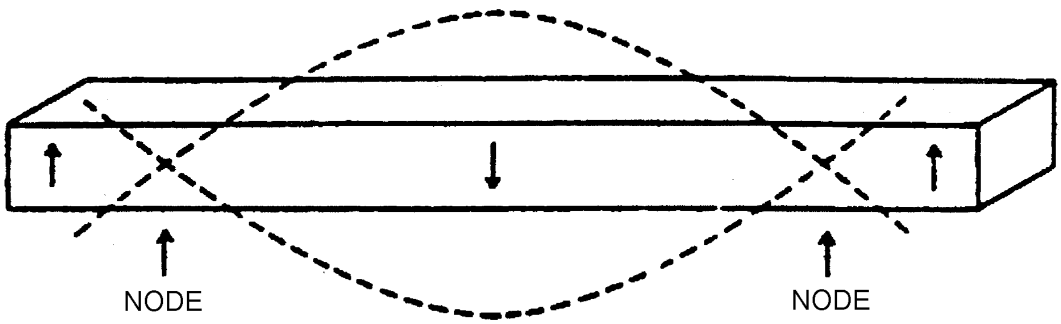
$$f_{flex.} = \frac{20.2h}{l^2} \sqrt{\frac{E}{\rho}} \tag{B-1}$$

$$f_{long} = \frac{h}{2l} \sqrt{\frac{E}{\rho}} \tag{B-2}$$

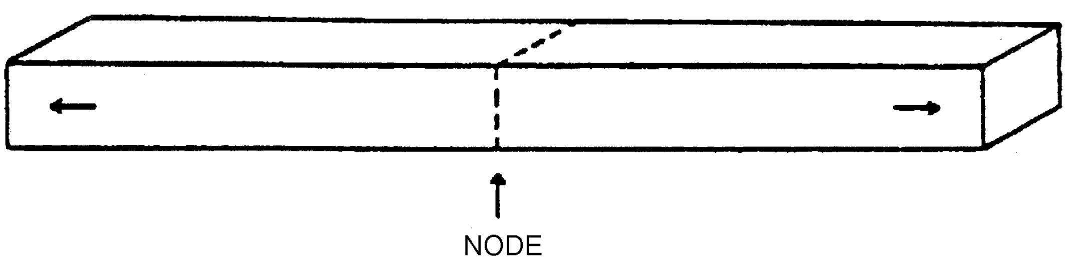
where

f = natural vibration frequency (Hz)

h = height or depth of the bar (in.)



a. Flexural mode



b. Longitudinal (extensional) mode

Figure B-2. Fundamental mode of vibration of a rectangular bar

l = length

ρ = density

If the natural vibration frequency is measured, the Young's Modulus of the bar can be obtained from Equation B-3, which suggests that Young's Modulus E is closely related to the natural vibration frequency. Young's Modulus is one of the important parameters for bar-like members such as beams in bridges. Young's Modulus for a square bare is calculated by

$$E = \frac{0.00245 f^2 l^4 \rho}{h^2} \tag{B-3}$$

(d) Real solids are never perfect; therefore, some of their mechanical energy is always converted into heat. This will lead to a vibration damping. Measurements of the vibration damping may provide reliable information for structural damage assessment.

(e) Mode shape is related to the structure properties. For the ideal solid bar mentioned above, the mode shape is very narrow with a high peak. But for more complicated structures, such as bridges, the mode shape depends on the mechanical properties and the geometric form of the structure.

(f) Hearn and Testa (1993) present a general equation of free vibration motion for an undamped elastic structure.

$$[K - \omega^2 * M]\ \{\phi\} = o \tag{B-4}$$

where

K = stiffness matrix

M = mass matrix

ω = resonant frequency

ϕ = the vibration mode shape

A perturbation of the structure is considered in which a small change in stiffness [ΔK] produces small changes in eigenvalues $\Delta(\omega^2)$ and in vibration mode shapes $\{\Delta\phi\}$, making the equation for the perturbed form

$$[(K + \Delta K) - (\omega^2 + \Delta(\omega^2))M]\{\phi + \Delta\phi\} = 0 \tag{B-5}$$

Equation B-5 clearly shows the relation of the stiffness change with the changes of the natural frequency and mode shape.

(2) Applications.

(a) A partial list of physical quantities that may be measured by these techniques is given in Table B-2. The experimental results of the dynamic Young's Modulus by the vibration technique can be found in (Wolfenden et al. 1989).

Table B-2
Physical Quantities Typically Measured by Resonance Vibration

Length, width, thickness diameter
Modulus of elasticity
Shear Modulus
Poisson's Ratio
Density
Modulus of rupture
Discontinuities or other inhomogeneities

(b) Resonance of a structure is reached when the frequency of an applied vibration force produced by piezoelectric transducer or electromagnetic vibration matches the natural frequency of vibration of the structure. Damage which plastically deforms a member would also be expected to change the stiffness and the frequency of resonance. A loss of stiffness may be detectable as decrease in the observed resonant frequency of the member.

(c) Many types of discontinuities and defects have been reported to have been detected in structures using the vibration dynamic method. This capability is usually carried out by the vibration interrogation of an undamaged structure or assembly at sufficient frequency levels and modes to establish trend data. By comparing the vibration scan of an identical part with this known reference, or by comparing the vibration scan for a given structure with time, one can detect whether there has been a change. The relative magnitude of change can be an indication of damage. Vibration dynamic techniques have been developed specifically to detect discontinuities and defects in various materials.

(d) A successful technique relevant to the vibration testing method was developed by West (1982 and 1986) for the space shuttle orbiter body flap test specimen. Several damage sites that were not detected by conventional NDE techniques were correctly identified by this technique. West's technique can locate damage in certain types of structures reasonably well, but it is unable to determine the extent of the damage.

(e) Two areas that have received considerable attention in recent years are civil engineering structures and offshore oil platforms (Yao 1982 and Yoa et al. 1982). The goal of the work was to define a method of assessing the structural integrity of buildings after their exposure to overload.

(3) Inspection of bridges.

(a) Civil engineering structures such as bridges, buildings, and dams have many natural frequencies below 100 Hz (Billing 1984). A high-powered hammer has been used to excite the resonant vibrations of these structures. Partly based on this information, Beliveau and Huston used an impact hammer as an exciting source to test a full-scale pedestrian bridge (Beliveau 1987 and Beliveau and Hutson 1988).

(b) The bridge tested is located on a bicycle path over Route VT 127 North of Burlington, Vermont. It has a span of 54.86 m (180 ft) between abutments and a treated timer deck width of 3.40 m (11 ft 2 in.) between center lines of the two main 0.91-m (36-in.) girders and cable-stay system. The cables have a diameter of 34.93 mm (1-3/8 in.), and the bottom flanges of the girders are 0.56 m (1 in. by 10 in.) plate.

(c) The equipment brought to the bridge site operated solely on batteries and included four accelerometers, a 53.38 N (12-lb) impact hammer, and a seven-channel frequency modulated tape recorder. The bridge was instrumented on three trips: first, for impact testing along the bridge centerline; then, for ambient vibration on a windy day; and lastly, for impact testing along one of the two main girders.

(d) The impact signal and two vertical acceleration signals were stored during the inspection on three channels of the tape recorder for further analysis in the laboratory. For center line testing, the hammer and accelerometers were located at the center of nine cross stringers located 5.64 m (18.5 ft) apart. For the torsion test, the impact hammer and accelerometers were located on two main girders at the ends of the nine cross members joining the two main girders. A four-channel spectrum analyzer was used to perform the data analysis.

(e) An average of three or four impact tests were used to arrive at a frequency response function of a particular accelerometer subjected to an impact load at another or the same location. These were then combined in the polyreference technique to obtain a best fit of the sum of complex exponential to the inverse Fourier transform of these frequency response functions. The natural frequencies of the bridge for the vertical and torsional vibrations are calculated by a similar method given by Hearn and Testa (1993). The experimentally obtained resonance frequencies are consistent with the theoretical results. The study indicates that the vibration dynamic method can be used to assess bridges. However, no further structural damage assessments using this method have been reported by the same investigators.

(f) The dynamic method has also been used for safety inspection of prestressed bridges in Austria (Flesch et al. 1988). The basic concept is the same: damage of the structure will lead to deviations of the dynamic parameters from the virgin state. These deviations can be used in a global manner to assess damage. In this report, emphasis was put on the aspects of theoretical model and software.

(g) Recently, Bagdasarian (1994) reported new progress on assessing the structural integrity of bridges through vibration monitoring. Recent studies at the University of Connecticut have shown that monitoring a bridge's dynamic characteristics is feasible. Laboratory testing on a bridge model developed a bridge "signature" comprising the bridge's natural frequencies and mode shapes. Changes in the "signature" correspond to changes in the model's structural stiffness. Therefore, these components of the "signature" (the natural frequencies and mode shapes) could be used to evaluate the structural condition of the bridge.

(h) A prototype monitoring system was developed by Vibra-Metrics, Inc., for placement on an actual Connecticut bridge. The monitoring system consists of sixteen accelerometers, two cluster boxes, and a sentry unit that houses a computer.

(i) The accelerometers act as sensors for detecting the bridge's vibrations. They are magnetically attached to the bridge girders and positioned throughout the floor plan of the bridge as shown in Figure B-3.

(j) The signals received by sensors in time domain from the vibrating bridge are transformed into the frequency domain by the monitoring system software. The frequency spectra are imported into the DADiSP program, where they are analyzed to determine the natural frequency peaks for monitoring purposes. Figure B-4 shows the natural frequencies and mode shapes of signals from sensors at different locations. Spectrum clean-up techniques are designed to enhance the appearance of the frequency spectrum. Cleaning a spectrum enables one to identify natural frequencies with less difficulty, thus allowing for the determination of changes in the natural frequencies indicating structural deterioration of the bridge.

c. Ultrasonic testing method.

(1) Principle.

(a) Ultrasonic waves are simply vibration waves with a frequency higher than the hearing range of the normal human ear (i.e., 20 kHz). The pioneer work in ultrasonic testing was accomplished by Langevin of France, who experimented with ultrasonic submarine detection methods during World War II. Now, most practical ultrasonic discontinuity detection is carried out with frequencies from 200 kHz to 20 MHz. Ultrasonic waves with 50 MHz or

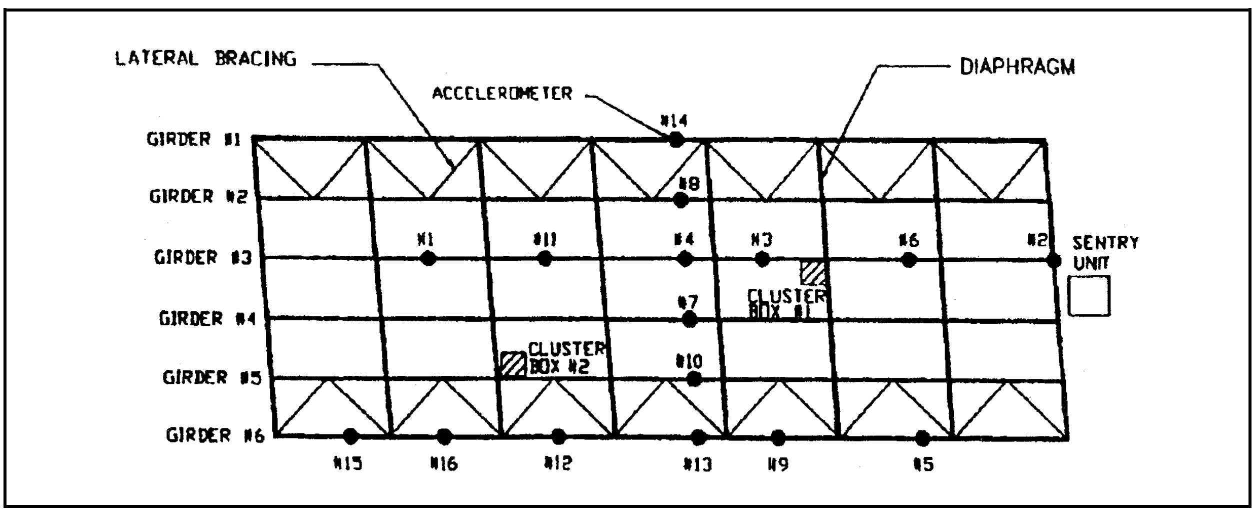


Figure B-3. Bridge floor plan with accelerometer locations

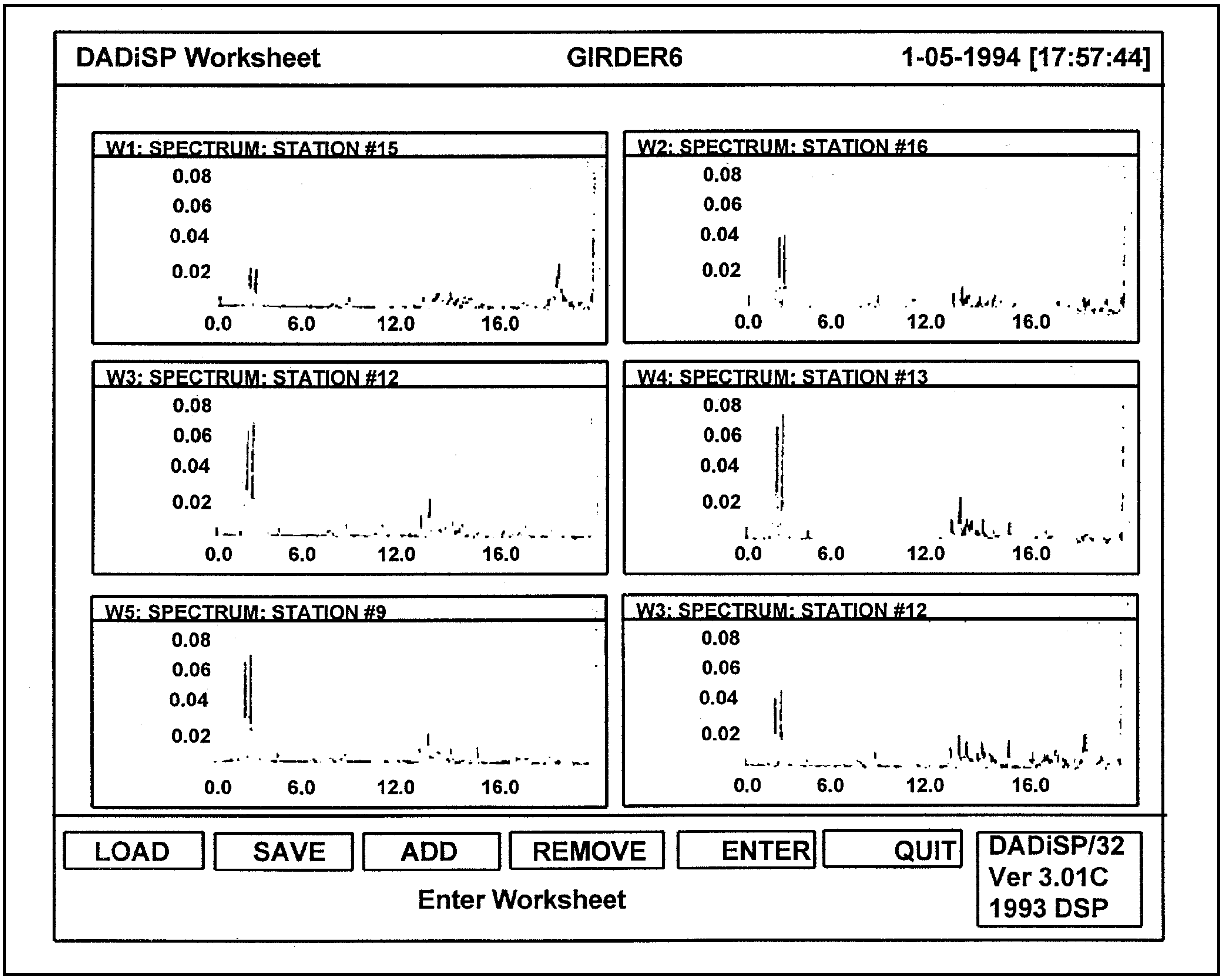


Figure B-4. Typical worksheet

higher frequencies are sometimes used in material property investigations.

(b) Ultrasonic inspection is accomplished by using electronically controlled pulses introduced into a material through a transducer. The ultrasonic energy then travels within the material, finally reaching an outer surface where the ultrasonic waves are received by the same or another ultrasonic transducer. Materials with discontinuities are diagnosed from the characteristic of the received ultrasonic energy. In this method, the wave intensity and the transit time are measured (e.g., on the screen of a CR tube as shown in Figure B-5). Perfect material without defects is assumed in Figure B-5(a), where the first pulse on the CR tube screen is from the exciting pulse, and the second pulse measures the transit time in the material sample. When a discontinuity exists in the material, the pulse due to the discontinuity reflection can be found, as shown in Figure B-5(b). The intensity of the flow echo is directly related to the discontinuity properties, and the position of the discontinuity echo reflects its locations. Variance in the discontinuity properties of fatigue cracks in bridge beams using ultrasonic methods has been reported by Hearn and Cavallin (1997). In most cases, one ultrasonic transducer (or probe) is used in the inspection. This method is also called A-scan presentation, furnishing a one-dimensional description for a given test point Figure B-6(a).

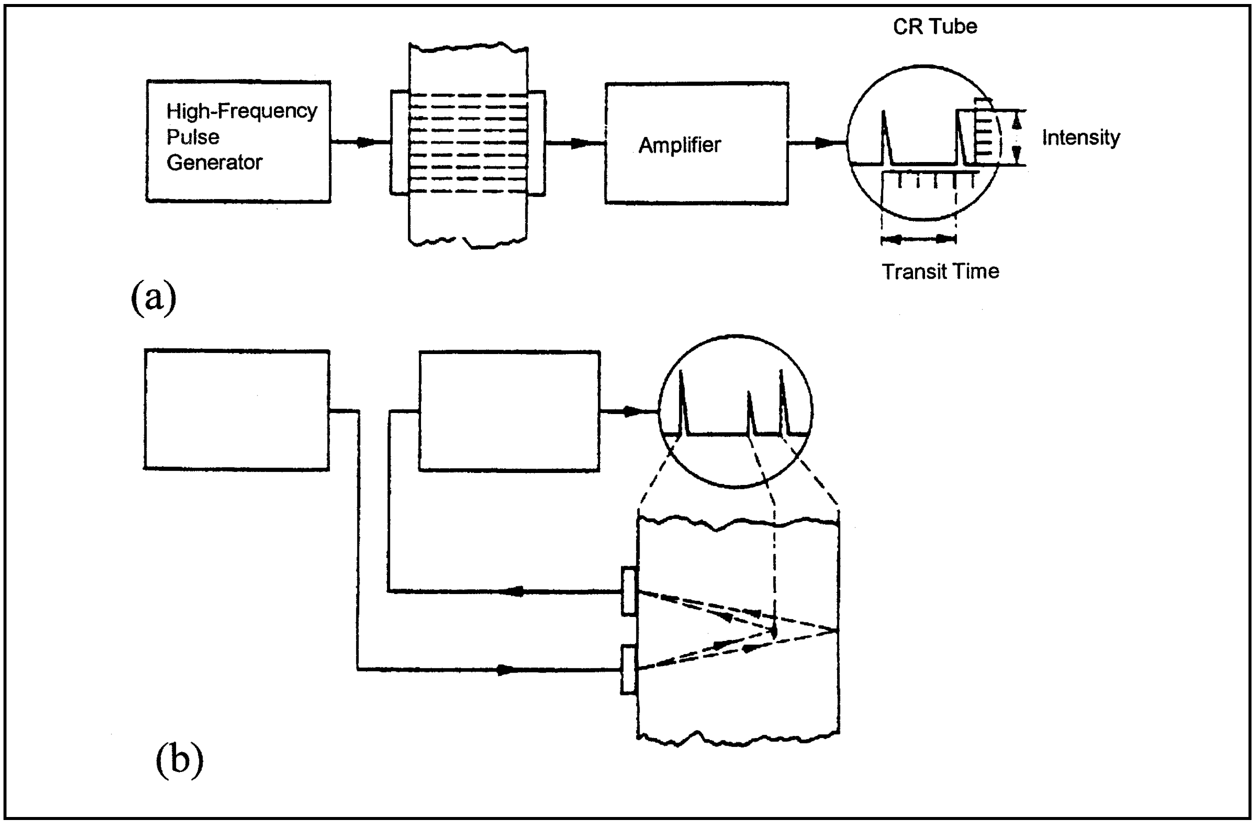


Figure B-5. Intensity transit-time or pulse transit-time method, (a) with sound transmission, (b) with reflection

(c) In the so-called B-scan method, the location (depth) of a discontinuity in a specimen is represented by echo position (usually along the vertical direction) and the amplitude of the discontinuity echo by the brightness, as shown in Figure B-6(b). In the case of two-dimensional (area) scanning of a test piece (e.g., a plate), the test results can be presented by means of a C-scan Figure B-6(c). This method furnishes a top view of the test piece from the scanned surface with plotted flaw projection points.

(d) Some of the advantages of ultrasonic methods are as follows: discontinuities can be detected in metallic and nonmetallic materials; discontinuity distance may be measured from the material surface; discontinuities can be located in very thick materials; only single-surface accessibility is required; both internal and surface discontinuities may be detected; discontinuity imaging is possible, and material properties can be measured. The ultrasonic technique has rapid testing capabilities, and portable instrumentation is available for field testing. Equipment for automatically recording inspection results is available, and the inspection costs are relatively low.

(e) Conversely, there are some disadvantages of ultrasonic testing: there may be difficulties incoupling energy to rough surface; it may be impractical to inspect complex shapes; flaw imaging is complex; and special scanning systems may be required for inspecting large surfaces.

(2) Applications.

(a) Computer-controlled multifunctional ultrasonic instruments for detecting discontinuities in materials have been highly developed (Wooh and Daniel 1994). These techniques can be used to detect cracks, voids, and other abrupt

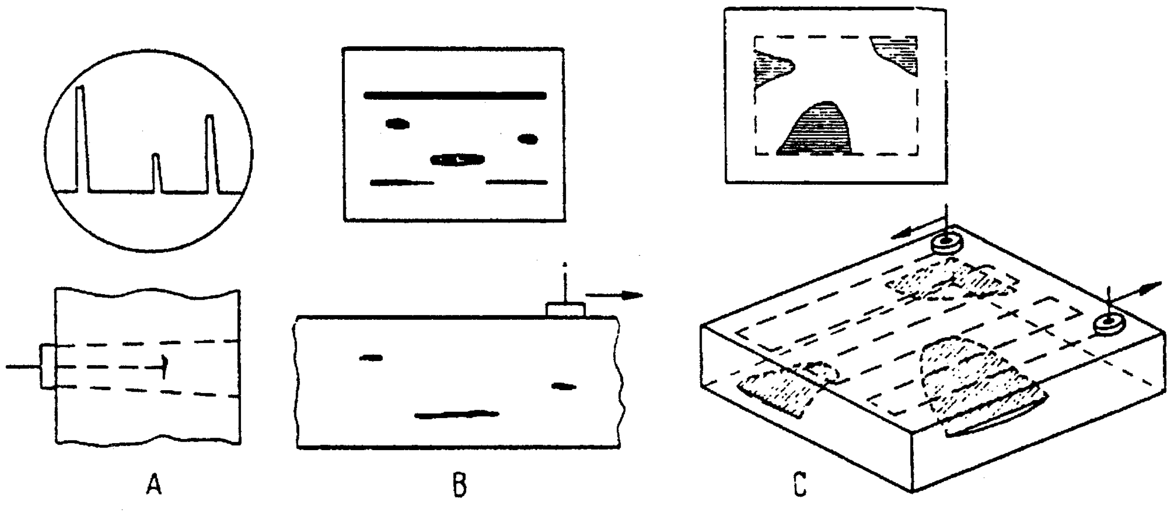


Figure B-6. A-, B-, and C-scan presentation and scanning method

discontinuity or lack of homogeneity in metallic, nonmetallic, and composite materials (Krautkrämer and Krautkrämer 1977, Bray and McBride 1992, Wooh and Daniel 1994, Thavasimuthu et al. 1993, Cruby and Colbrook 1992, and Berger 1992). On-line weld monitoring using ultrasonics is also well developed (Stares et al. 1990; Bull et al. 1995; and Prikhod'ko and Fedorishin 1993).

(b) Major limitations of these techniques involve attenuation characteristics of certain materials, access problems, very tight cracks, and complex geometric configurations. Even with these limitations, ultrasonic discontinuity evaluation technology is very effective when properly applied. Some typical applications are listed in Table B-3.

Table B-3
Some Sources of Acoustic Emissions

Raw materials	Adhesive bonds
Weldments	Aircraft
Castings, forging	Spacecraft
Pipe	Nuclear reactors
Seamless tubes	Ships
Railroad wheels, rails, and axles	Bridges

(c) Examples of applications which are related to the structural inspection of bridges include the following:

- **Normal-beam inspection of bars and plates**. One of the most common tests performed with ultrasound is the inspection of structural plates and bars for interior discontinuities and corrosion using a normal-beam and longitudinal-wave probe. These tests are applied to both plain material and fabricated members.

A typical A-scan, digitized RF display of a normal-beam inspection is shown in Figure B-7(a). The test sample is an aluminum bar 76 mm thick. With a sampling rate of 20 MHz and an expansion of 1, the time base is 36 μs. The echo occurring at 15.7 μs (point A) past the main bang indicates a discontinuity at approximately 49 mm below the probe. The back echo appears at 24 μs (point B) beyond the main bang.

The horizontal bar above the discontinuity echo (point A) indicates a gate starting at 17.8 μs and 2.95 μs in length. One use of a gate is to select a signal for frequency analysis as shown in Figure B-7(b). The output shows the peak power

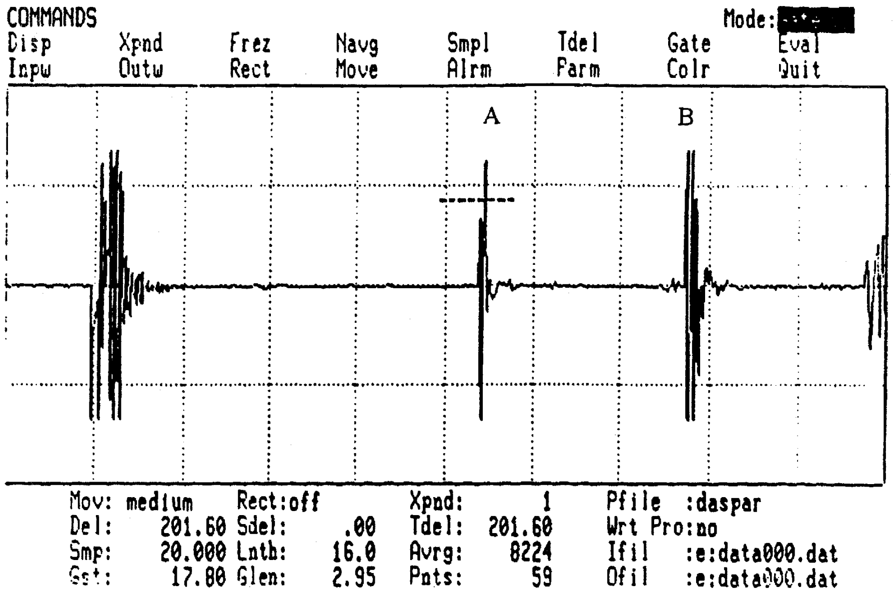


Figure B-7(a). Typical digitized RF display of test of aluminum bar 76 mm (3 in.) thick. Time base is 3.6 E-6x/div.

spectrum frequency to be 5 MHz, which agrees with the frequency of the probe. Other information shown in the figure describes additional parameters used in signal analysis (Bray and Stanley 1984).

- **Welded joints**. The following types of manufacturing defects can be detected in welded butt joints using ultrasonics: slag inclusions, pores, lack of fusion (cold shuts), lack of penetration, and cracks. Figure B-8(a) shows the ultrasonic testing of a welded joint with normal longitudinal probes, and Figure B-8(b) illustrates testing of a welded joint with transverse probes. Figure B-9 shows testing of fillet welds.

(3) Inspection of bridges.

(a) The ultrasonic techniques are used to inspect bridge components such as beams, girders, and chords before a bridge is completed. The allowable discontinuity size in the components is highly restricted during fabrication. However, during shipping, handling, and erection of bridge components, new cracks may grow. Therefore, it is suggested that bridge components should be inspected both during and after construction.

(b) In Japan, ultrasonic testing is utilized for nondestructive in-process evaluation. As a rule, automatic ultrasonic testing inspection is performed for welded chord members. Ultrasonic testing of in-service bridges is time-consuming. To date, no real-time structural damage assessment of bridges is reported.

d. Acoustic emission method.

(1) Principle.

(a) Acoustic emission (AE), sometimes called stress wave emission, is a transient mechanical

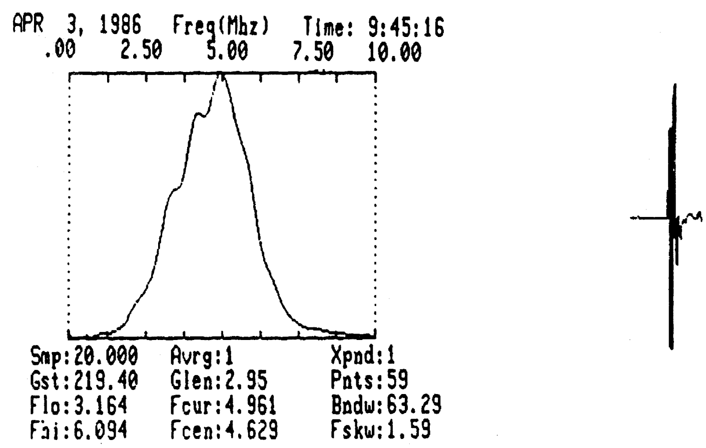


Figure B-7(b). Power spectrum for ultrasonic signal

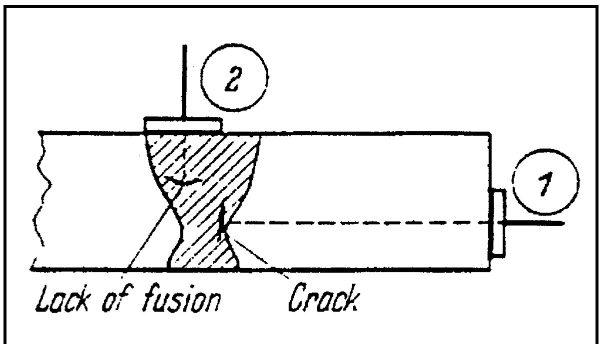


Figure B-8(a). Testing of welded joint with normal probes

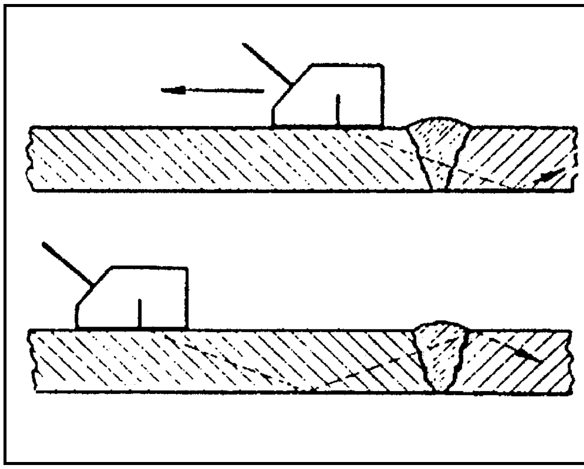


Figure B-8(b). Test of welded joint with zigzag transverse waves

vibration generated by the rapid release of energy from localized sources within materials. Stress or some other stimulus is required to release or generate emissions. Emission energy levels can range from the motion of a few dislocations in metals to that required to cause catastrophic cracking of structures. Some stimuli causing acoustic emissions are given in Table B-4.

(b) Acoustic emission signals cover a wide range of energy levels and frequencies but are usually considered to be of two basic types: burst and continuous. The term *burst* is a qualitative description of emission signals corresponding to

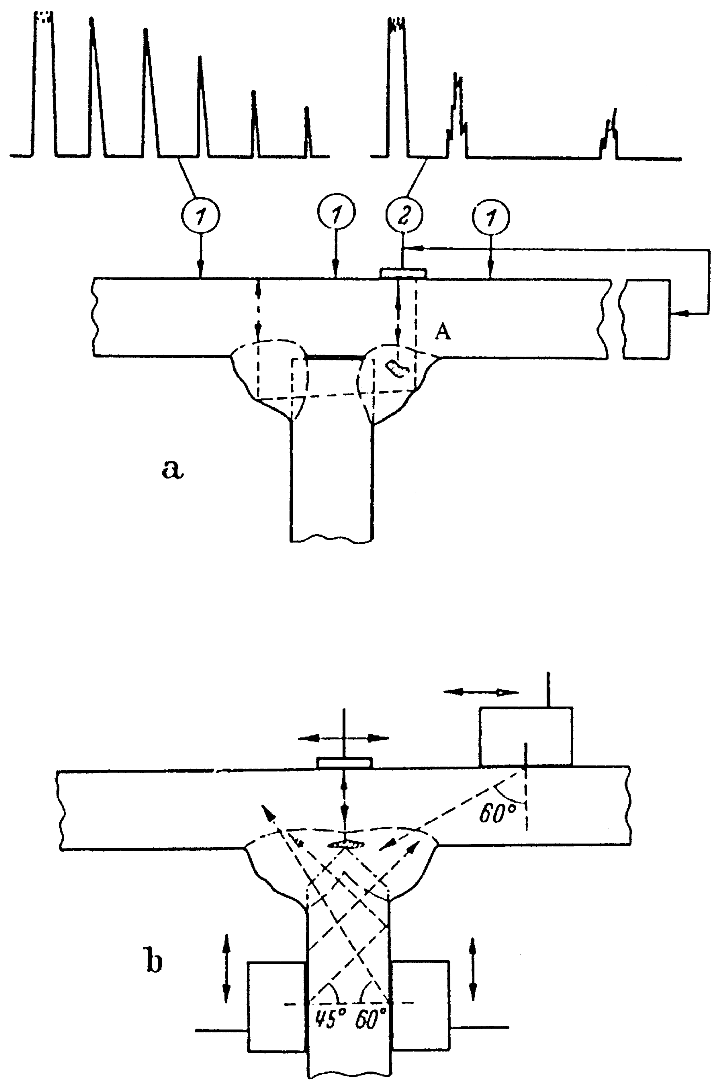


Figure B-9. Testing fillet welds; (a) joint not welded through, (b) joint welded through (K-joint)

Table 4
Some Sources of Acoustic Emissions

Crack initiation and growth
Dislocation movements
Twinning
Phase changes
Fracture of brittle inclusions or surface films
Fiber breakage, crazing, and delaminations in composites
Chemical activity

individual emission events. The term *continuous emission* is a qualitative description for an apparently sustained signal level from rapidly occurring emission events. Emission frequencies range from below to well-above the audible range for humans. But most practical AE monitoring is accomplished in the kilohertz or low-megahertz range.

(c) Although emission is characterized as burst or continuous, signals of either type may propagate in any of the standard ultrasonic modes (i.e., shear, longitudinal, or surface waves). Furthermore, a single emission event can generate waves having more than one propagation mode.

(d) A wide range of transducer types has been used to sense acoustic emission from materials, structures, and industrial equipment. The types of AE sensors include accelerometers, piezoelectric transducers, capacitive transducers, optical/laser sensors, microphones, strain gauges, magnetic-strictive sensors, etc.

(e) The most widely used method of quantifying AE signals is the ringdown counting technique, which measures the characteristics of the emitted signal as its amplitude decays. For a typical sinusoidal AE pulse, an amplitude threshold is established for the acceptance of signals, and the number of signals exceeding this threshold is automatically counted by the instrumentation system. Signals crossing the threshold are usually plotted as a function of load, stress, time, or other parameters. They may be plotted as the count rate versus stress, or the plot may be of the total or cumulative count versus the selected parameter. The data presentation techniques are illustrated in Figures B-10 and B-11. The significant parameters used in characterizing acoustic emission

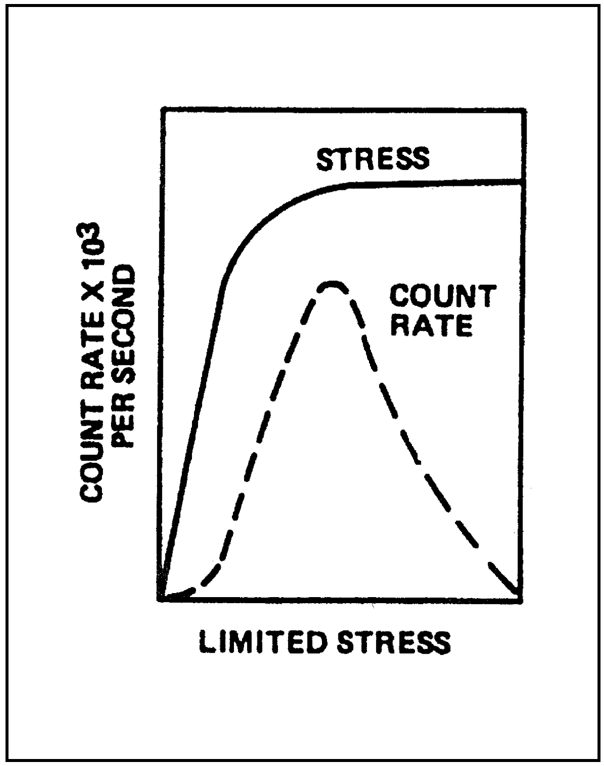


Figure B-10. Generalized count rate versus stress

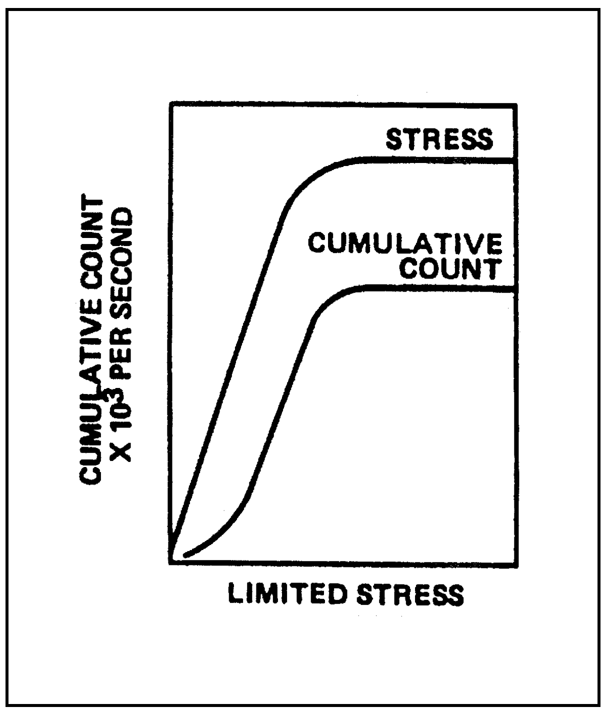


Figure B-11. Generalized cumulative count versus stress

events are peak amplitude, frequency, duration of signal above the selected threshold, number of counts per event, energy, and rise time. Some of these parameters are indicated in Figure B-12. These parameters are related to the various AE sources in different ways. For example, the AE count rate associated with plastic deformation at the tip of a crack may be expressed as (Muravin et al. 1993)

$$N = (ChK_{Imax}^2/\sigma_Y)\ dl/dn \tag{B-6}$$

where

C = a proportionality factor

h = thickness of the specimen

K_{imax} = maximum value of the stress intensity factor

σ_Y = yield point

dl/dn = growth rate of the crack length for loading cycle

(f) For engineering applications, it is more convenient to find out the relationship of AE count rate with the stress intensity factor range ΔK. For fatigue fracture in materials, Morton et al. (1974) and Bassim (1987) present the following equation:

$$N = A\ (\Delta K)^m \tag{B-7}$$

where A and n = experimental constants. This equation is similar to the well-known Paris law of fatigue-crack propagation (Paris et al. 1963):

$$dl/dn = C\ (\Delta K)^m \tag{B-8}$$

where

dl/dn = crack-growth rate

C and m = experimental constants

(2) Applications.

(a) The AE method has wide applications. It can be used to monitor changing material

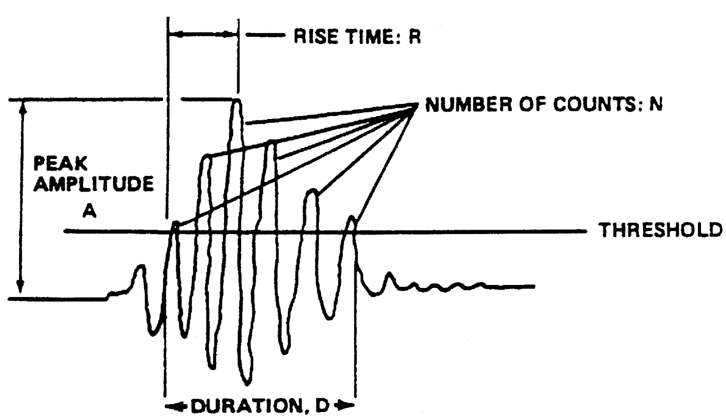


Figure B-12. Parameters used to characterize emission events

conditions in real time and to determine the location of the emission centers as well. Typical applications include on-board or onsite monitoring of aircraft, pressure vessels, tank welds, bridges, and civil engineering structures. In addition, corrosion and bearings in pumps and other rotating machinery such as hydraulic valves can be monitored. Simulated acoustic emission techniques are also useful for monitoring types of composite materials. Some recently reported applications can be found in Ramsamooj (1994), Yuyama et al. (1994), Glaser and Nelson (1992), and Fang and Berkouits (1994).

(b) The advantages of AE are rooted in the basic characteristic where the active defect emits a signal that will find a path to the monitoring sensor location. Since it is a passive technique, no equipment is required to excite a pulse. Further, the received signals may be recorded for remote or delayed analysis and for storage. The requirements for equipment mounted on the monitored structure may be rather small. Other advantages are that AE techniques are highly sensitive to crack growth, and locations of growing cracks can be determined.

(c) Additional advantages are the ability to monitor an entire system at the same time. With remote monitoring, the technique can be used in hostile environments. The item being tested usually can remain in operation during the process, and the entire volume of materials and structures can be inspected at a reasonable cost. It is also suitable for long-term in-service monitoring.

(d) Disadvantages of the technique include the requirement of stress or other stimuli to generate the acoustic emission event. Therefore, stabilized cracks cannot be detected with emission techniques. The size of cracks or other defects cannot be precisely determined. Some materials and certain tempers of other materials are not very emissive and are unsuitable for monitoring. Electrical interference and ambient noise must be filtered out of emission signals. Also, the multiple number of travel paths from the source to the sensor in complex structures can make signal identification difficult.

(3) Inspection of bridges.

(a) AE techniques were used in the 1970s to monitor some bridges (Pollock and Smith 1972; Hutton and Skorpik 1975). In the 1980s, extensive studies were carried out to use acoustic emission techniques for bridge inspections (Fisher and Wood 1988; Hopwood and Prine 1987; and Green 1988). It was reported that (Hopwood and Prine 1987) an experimental AE device, the Acoustic Emission Weld Monitor (AEWM), has been field tested on six bridges during the study. The device was also used to test three other bridges under separate contracts from state highway agencies. The AEWM was evaluated to determine if it could detect fatigue-crack growth on in-service steel bridges. The device rejects high background noise rates typical of bridges and detects and locates AE activity from known defects such as cracks and subsurface discontinuities. The AEWM functioned properly in every field test situation to which it was applied. The AEWM has demonstrated capability to perform AE tests on in-service bridges. It may also be used to detect hidden discontinuities or assist in making repair decisions concerning detected discontinuities. The AEWM and AE testing have been demonstrated to have the potential for low-cost inspection of critical bridge members.

(b) Some newly accomplished inspections of bridges by the AE techniques are also reported (Hariri 1990, Azmi 1990, Vannoy and Azmi 1991, and Gong et al. 1992). A comprehensive examination of characteristics of acoustic emission signals generated from steel beams (rolled and welded sections) and other steels used in highway bridge structures was made. The effective frequency range for monitoring highway bridges was established. In these inspections, the thickness and surface conditions of bridge components are varied. Crack lengths were measured at the time of data collection, and various acoustic emission parameters were plotted versus the stress intensity factor of the specimens. It was discovered that acoustic emission signal characteristics for the steel types used in highway bridges are similar although, the signals vary according to the thickness of the material. It was also discovered that the corrosion surface enhances the intensity of the signal, and paint layers do not have a significant effect on the attenuation of the AE signals.

(c) Recent inspection of steel railroad bridges by the AE method is presented by Gong et al. (1992) in which they demonstrate successes using AE to find new cracks, to identify active cracks, to validate the effectiveness of repairs, and to provide damage assessments to assist with repair prioritization.

(d) As given in Equation B-7, the stress intensity factor range ΔK for fatigue fracture is highly related to the acoustic count rate *N*. The typical relationships among the acoustic count rate, the crack-growth rate, and ΔK, based on laboratory tests of typical bridge steel, are shown in Figure B-13. It can be seen that the count rate increases as a crack grows, and for an active fatigue crack, the count rate presents an increasing slope under constant cyclic loading. This result indicates that a positive slope of the count rate over time during field testing may be used as a means of judging crack severity when compared to similar slopes obtained from laboratory tests on the same material. Table B-5 and Figure B-13 show a method of classifying fatigue cracks inbridge steel into five safety index levels based on the range of structure ΔK determined by AE monitoring. This approach has been effectively used in interpreting ΔK levels obtained from field monitoring and applying them to the prioritization of crack repair programs.

(e) The Monac multi-channel field AE-monitoring system is currently being used to

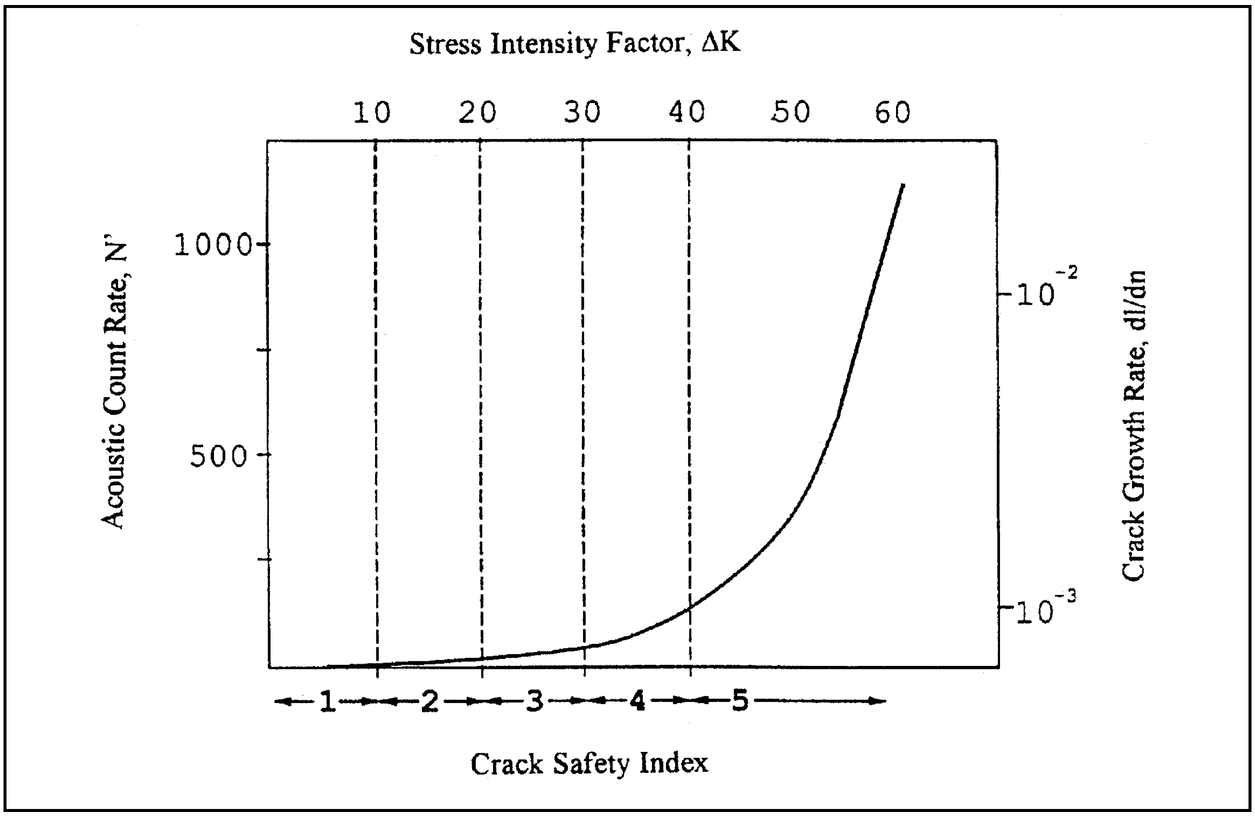


Figure B-13. Typical relationships among the crack safety index, crack-growth rate, count rate, and ΔK for bridge steels

Table B-5
Fatigue-Crack Characterization for Bridge Steels

Range of ΔK	Crack Safety Index	Crack Description
$0 \leq \Delta K < 10$	1	Minor defect
$10 \leq \Delta K < 20$	2	Slow crack growth
$20 \leq \Delta K < 30$	3	Requires repair
$30 \leq \Delta K < 40$	4	Dangerous
$40 \leq \Delta K$	5	Imminent failure

monitor 36 bridges under normal loading conditions. The system consists of surveillance units and an IBM PC control unit as shown in the Figure B-14 block diagram. A line driver and receiver are located next to each acoustic transducer to ensure the fidelity of weak acoustic signals after transmission over long cables. The monitoring distance can be up to 460 m (1,509 ft). All bridges tested utilized standard piezoelectric transducers with resonant frequencies of 200 kHz.

(f) In total, 353 locations have been monitored on 36 railroad bridges over three years of testing. Each location was monitored continuously from 4 to 10 days, during which time about 40 trains passed over each bridge. Table B-6 gives the results of this monitoring which located 116 active cracks; among them 14 cracks had a safety index of 3 and only one crack had a safety index of 4. No crack had a safety index greater than 4.

(g) Cracks were often found at the webs of floor beams near the upper corners of the connection angle with a stringer. In most cases, such cracks had initiated because of the bending moment on the stringer end. AE monitoring indicated that two such cracks had a safety index of 2. Many fatigue cracks were also found on the top flanges of stringers.

(h) It was found that welds were always the most crack-sensitive areas, possibly due to residual stresses and stress concentrations. Therefore, current recommendations for bridge maintenance and repair favor bolting and riveting rather than welding (Fisher et al. 1990).

e. Optical fiber method.

(1) Principle.

(a) Like an elastic waveguide, a fiber can guide high frequency electromagnetic waves (optical waves) (Kao 1988 and Katsuyana and Matsumura 1989). In a perfect symmetric and homogeneous fiber waveguide, the waveforms of guided modes propagate undisturbed along the waveguide axis. However, a deformation or inhomogeneity in fiber geometry may cause coupling among different modes, resulting in power transfer. In particular, the guided modes may be coupled to radiation modes, which are not confined. The resulting power transfer represents an attenuation. Similarly, any deformation of material attaching the fiber can also give rise to the mode coupling and guided wave attenuation. Therefore, the received optical wave in fiber can be intensity modulated by the deformation of the outside material. The guided wave can also be phase modulated due to the change of its geometric form which is caused by the strain or deformation on the outside material.

(b) An optical fiber embedded in structures will deform together with the structure. The light passing through the optical fiber can be modulated either in intensity or in phase. This effect has been implemented in a form called “Smart Strain.” By analyzing the changes of light intensity or phase transmitted by embedded fiber, dangerous strain levels in the structure as well as failure of material may be detected. A system of such optical fiber sensors embedded in a structure could act as the “nervous system” of the structure.

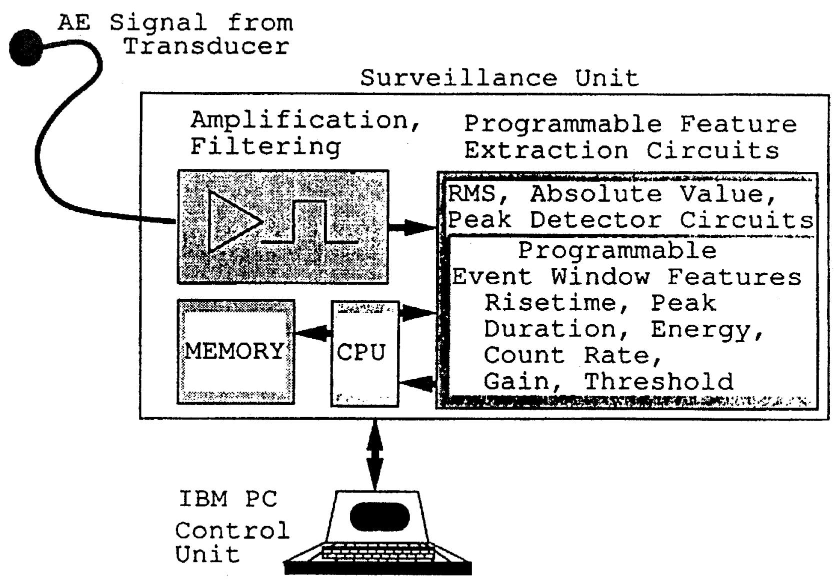


Figure B-14. Block diagram of the Monac acoustic monitoring system. RMS = root mean square

(c) A typical experimental arrangement for an optical fiber sensor is shown in Figure B-15 (Brennan 1988). The output of a laser diode was used in the input into the optical system which is configured as a polariscope. The circularly polarized light output from the combination of polarized laser output and quarterwave retarder is injected into the optical fiber. Strain induced by beam deformation in the fiber will produce a change in the polarization state at the output. This is measured by the second polarizer acting as an analyzer and the photo-diode. The retardation between the two principle polarizationaxes is seen as an intensity variation as measured by the photo-diode.

(d) Figure B-16 illustrates another example of optic fiber sensor (Sharma et al. 1981). This is similar to the two-arm interferometer. The fiber numbered 5 in Figure B-16, is subjected to the external influence, but the fiber numbered 4 is isolated. Any change of the light phase in fiber number 5 will result in the interference fringe displacement. The advantages of optical fiber include its small size, light weight, faster data speed, immunity from electromagnetic induction, positioning, and lower cost.

(2) Applications. Optical fiber sensors have been widely investigated (Asawa et al. 1982; Marvin and Ives 1984; Lapp et al. 1988; Maria et al. 1989). A special conference on fiber optic smart structures and skins was held with more than thirty papers presented at the International Society for Optical Engineering (1988). Following is a brief introduction of some applications of the optical fiber sensors.

- **Mapping strain field**. Optical fiber sensors can be used to provide evaluation of the

Table B-6
Results of Railroad Bridge Monitoring

Bridge Number	Bridge Type	Number of Monitoring Locations	Number of Active Cracks	Crack Safety Index				
				1	2	3	4	5
1	TTS	8	2	1	1			
2	TPGV	4	1		1			
3	TPG	6	3	1	1	1		
4	DPG/TPG	7	2		2			
5	TPG	6	0					
6	TTS/TT	8	3	2	1			
7	TT/TPG/TTS	8	1		1			
8	DPG/PYT	7	1		1			
9	TPG/TT	5	0					
10	DPG	5	1		1			
11	TT/DT/DPG	8	3		3			
12	TPG	6	4	1	3			
13	DPG/BM/DPGV	8	1		1			
14	DPG/DT	8	3	2	1			
15	DT/TT	8	6	1	5			
16	DPG/TPG	6	4	3	1			
17	DT	15	3	1	2			
18	TT	13	2		1	1		
19	TT	134	46	23	19	4		
20	TT	12	6	2	4			
21	DT	5	0					
22	TT	6	0					
23	TT	5	2	2				
24	DPG	6	3		3			
25	TT	8	2	2				
26	DPG	12	4	2		2		
27	DPGV	2	1			1		
28	DPGV	2	2		1	1		
29	DPG	3	1		1			
30	DPGV	2	0					
31	DT	6	1		1			
32	DPGV	2	0					
33	DPGV	3	2		1		1	
34	DPGV	3	2		1	1		
35	DPG	2	1			1		
36	DPG	4	3		1	2		

Bridge types: TTS = through-truss swing, TPG = through-plate girder, PYT = pony truss, DT = deck truss, TPGV = through-plate girder viaduct, TT = through-truss, DPG = deck-plate girder, and BM = beam.

state of strain in a structure, i.e., to map the strain field in real time (Measures et al. 1988). The reconstruction of the strain field may be achieved by using the information obtained from the field along a finite number of distinct paths (Figure B-17(a)). This is similar to the reconstruction problem in topography, where the inverse transform is used to obtain the scalar field distribution. The reconstruction of the strain field may also be made by using point fiber optic sensors (Figure B-17(b)).

- **Flight control and damage assessment**. The fiber optic system composed of a network of embedded sensors may be used to measure the location and extent of damage that may occur during flight, as well as structural integrity prior to take off (Udd 1988). This system could be used in combination with the flight control system to ensure that the aircraft readjusts into a safe flight envelope. The sensors could also be used to measure such parameters as engine temperature, shock position, structural loading, and temperature and pressure distributions augmenting the flight

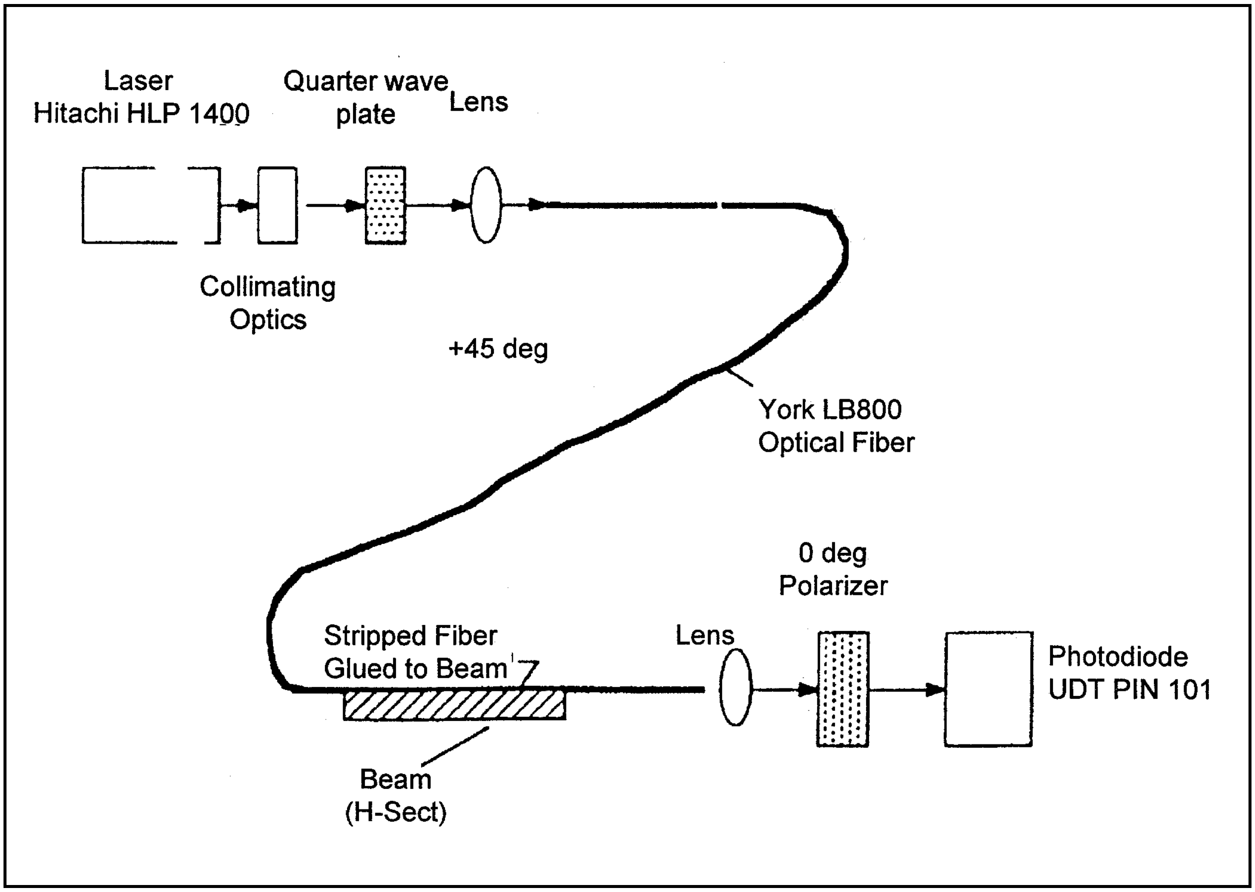


Figure B-15. Optical arrangement

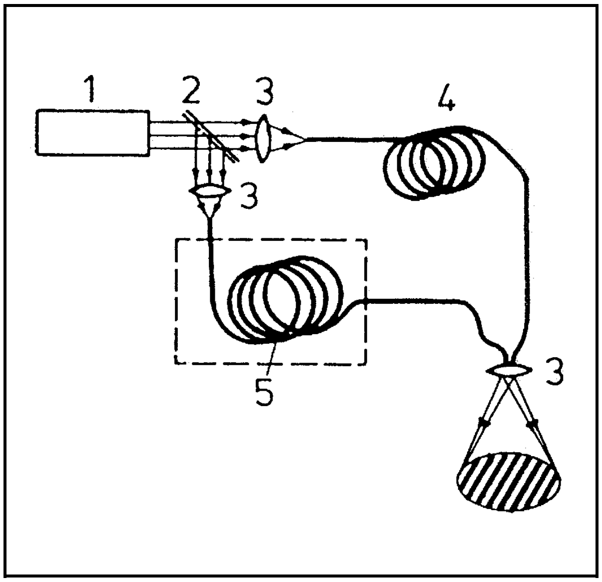


Figure B-16. Illustration of the two-arm interferometer

control system. This concept could be applied to measuring the location and extent of damage to an in-service bridge.

- **Vehicle detection and vehicle health monitoring**. The vehicle detection and vehicle health monitoring system requires the installation of 55-cm-long sensing elements on roadways (Tardy et al. 1989). To prevent sensor damage, cable elements are laid into grooves made in the roadway. The laying process consists of placing epoxy resin at the bottom of the groove, installing the sensor cable, then filling the groove with elastomer. Different groove depths have been made. A reflective coating on the end face of the sensor fiber allows the polarization effect to be interrogated by a single fiber with Y coupler. When a vehicle passes over the sensor, a signature of characteristics is developed. The first fringe

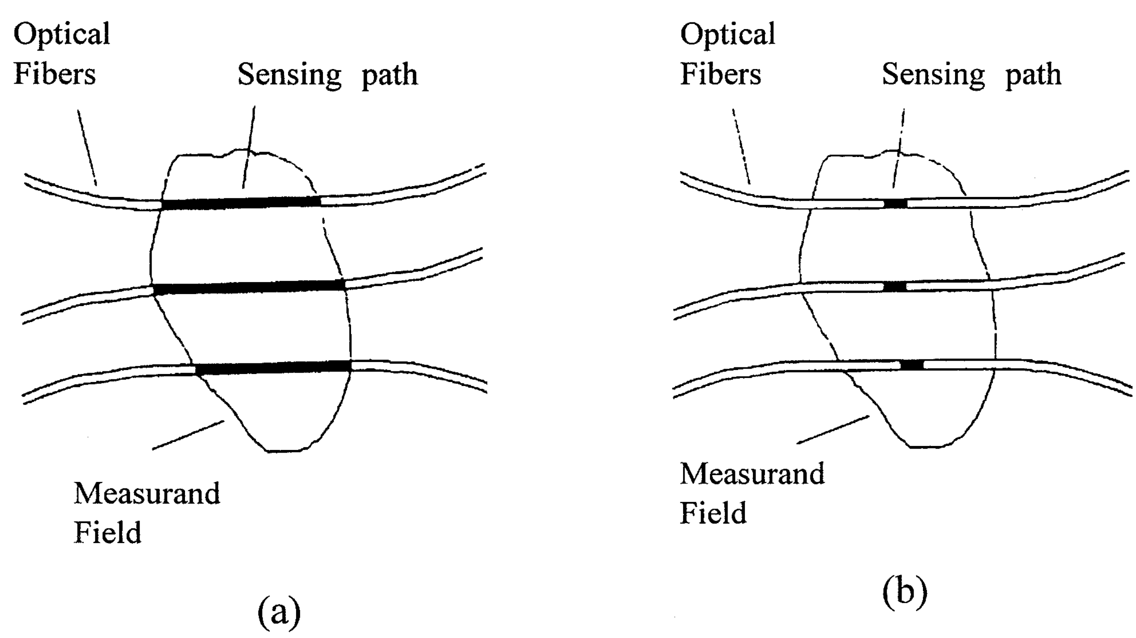


Figure B-17. Reconstruction of the strain field: (a) integrating fiber optic sensors traversing a measured field, (b) using point fiber optic sensors

shift corresponds to the increased loading created by the vehicle. A continuous signal indicates a quasistatic pressure, while the second fringe shift corresponds to the escape of the vehicle from the sensor. The weight and speed of a moving vehicle may be identified from the fringe number.

- **Concrete structure testing**. In one example, 14-cm-long fiber-optic sensing elements have been embedded in concrete test pieces to determine their response to external pressure (Tardy et al. 1989). Before placing the sensors in concrete, the ribbons outside the sensor are covered with epoxy resin and sand as shown in Figure B-18. These new sensors have been tested in a simple compressive test using a polarimetric apparatus. First readings indicate a sensitivity loss and fringe visibility reduction at the output end of the fiber. The high value of the hardening stress is due to the shrinking phenomenon of concrete. Sensor desensitization is accomplished by loading the test-piece in a perpendicular plane to that of the ribbons. The observation sensor response is shown in Figure B-19, where the stress axis origin corresponds to the hardening pre-load. The fringe numbers, which are related to the phase change of the propagating light in the optical fiber versus pressure, are in agreement with the theoretical values. If fiber optic sensors are properly embedded in critical parts of bridges, they may be used for structural damage monitoring and structure integrity assessment.

B-3. Summary

a. A review of state-of-the-art techniques for real-time damage assessment of bridge structures is provided. Of these methods reviewed, the vibration dynamic and AE techniques have been used in the real-time structural damage assessment of in-service bridges on public roads. These two methods have different physical bases.

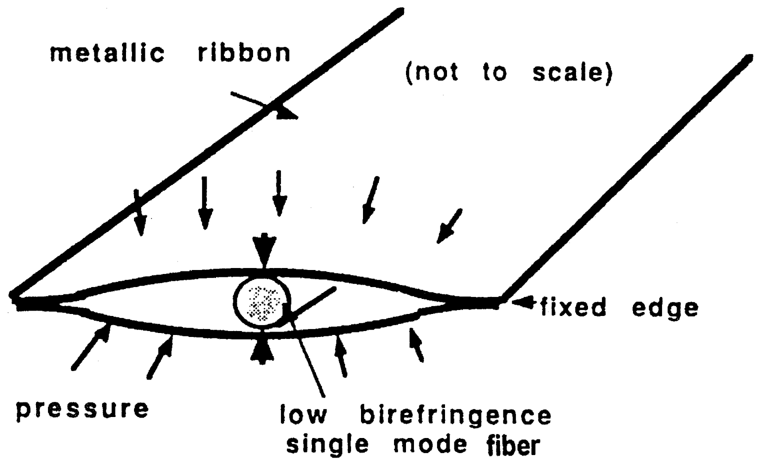


Figure B-18. Sensing structure

b. Every bridge has its own natural vibration (or resonance) frequencies, which are related to the materials, structural geometry, and integrity of the bridge. If some components of the bridge are damaged, the resonance frequencies and mode shapes will change. The bridge signature can be used to evaluate the bridge integrity. If cracking occurs on a bridge, acoustic emission signals are emitted. AE techniques have been used for fatigue-crack detection of bridges. The greatest advantage of AE monitoring over the other NDE methods is its ability to detect active cracks and to classify the severity of crack damage.

c. Although there are no published papers on the use of optic-fibers to detect bridge damage, optic fiber smart sensors have great potential for monitoring damage incurred in bridge members. All of the methods discussed are on the "cutting-edge" of technology for use in assessing bridge damage. Experimentation of these methods in real-time bridge damage assessment is still under investigation.

(1) Each critical component of a bridge should be inspected by applying the most appropriate NDE technology (e.g., visual, eddy current, liquid penetrant, magnetic particle, ultrasonic testing, or radiographic inspection) to discover any defects in the components. Members in tension, localized areas around stress concentrations, and areas where a three-dimensional state of stress or high constraint occurs should be considered in the inspection plan.

(2) The vibration dynamic method can be effectively used to make real-time damage assessment of bridge integrity. Each bridge has a special "signature" including resonance frequencies and mode shapes. Some lower resonance frequencies are simulated easier, since they have large vibration amplitude and are

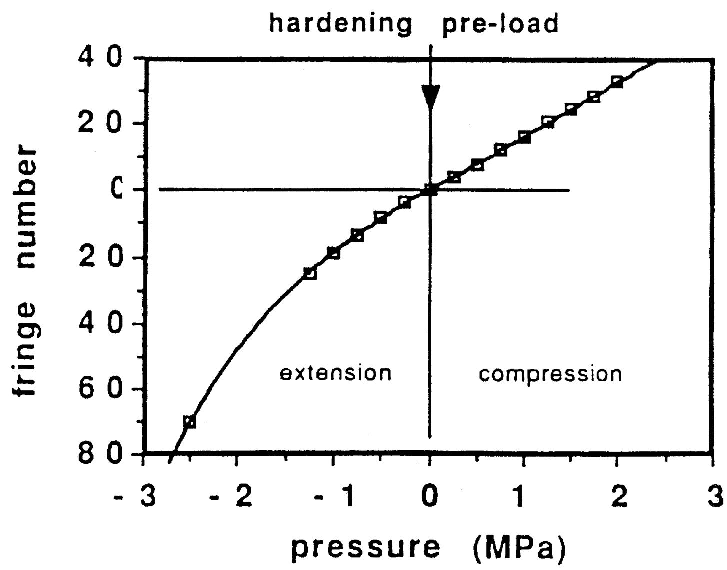


Figure B-19. Experimental response from sensor embedded in concrete

separated from other resonance frequencies. Computer simulations or bridge models may be useful in determining the best location to place transducers to sense the vibration of signals.

(3) AE techniques have engaged the interest of many scientists and engineers in real-time bridge damage assessment. AE signals are developed during crack growth and can be monitored on a real-time sources to the sensor, the signal identification can be difficult. A combination of AE with the vibration or ultrasonic technique may be necessary to completely evaluate a bridge.

(4) The optic fiber method has been widely used to inspect aeronautical facilities. It has not been extensively used for nondestructive evaluation of civil structures such as bridges and buildings. Several advantages (e.g., its small size, faster data speed, and low cost) of the optic fiber method are attractive for bridge inspection. Application of this method to a bridge would require tightly binding optic fibers to the critical bridge members and monitoring the change of optical intensity or phase at the output end.

d. A new application of fiber optics is in crack imaging. It is reported that fiber optical equipment can be used to provide clear and high resolution images of remote cracks contained within critical members (Wilson 1983). This equipment is reported to be easy to handle and operate. Fiber optic techniques have traditionally been applied to the inspection of machined parts on mechanical assemblies, but may also be applicable to the real-time inspection of small areas on critical structural members of a bridge.